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Characteristic of size distribution of rock chip produced by rock cutting with a pick cutter

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ABSTRACT

Chip size distribution can be used to evaluate the cutting efficiency and to characterize the cutting behavior of rock in cutting and fragmentation process. In this study, a series of linear cutting test was performed to investigate the effect of cutting conditions (i.e., cut spacing and penetration depth) on producing of rock chip and the size distribution of the rock chips. Linyi Sandstone from China was used for the linear cutting test. All rock chips were collected after LCM (Linear Cutting Machine) test, and the size distribution of the rock chips was analyzed using sieving test and image processing. Image processing can provide useful information of size distribution at low cost and time consumption. Coefficient of Rosin-Rammer distribution, coarseness index, coefficient of uniformity and curvature were determined by image processing for different cutting conditions. The size of rock chip was the greatest at the optimum cut spacing, and the results showed that the size distribution parameters were highly correlated with the cutter forces and the specific energy.

Keywords: Chip size distribution, Image processing, Linear Cutting Machine Test, Pick cutter, Rock powder, Cutting efficiency

1. Introduction

Mechanical excavation method has been widely used in many civil and mining projects, and its demand is rapidly increasing due to its numerous advantages in terms of safety, stability, high advance rate, less environmental impact and construction practice compared with the drill and blasting method (Jeong et al., 2014). Especially, the mechanical excavation is sometimes essential for the urban, subsea tunneling and subsea trenching.

It is important to estimate the cutter force and the cutting efficiency during rock cutting for optimizing the machine operation (Jeong et al., 2016). Size distribution of rock chips obtained in the rock cutting process can provide useful information to estimate the cutting efficiency. The chip size distribution is also required when using rock chips as aggregates and designing backup facilities of excavation machines. In addition, it is important to determine the optimum particle size for efficient processing of mineral resources in mining engineering application. Therefore, measurement of fragment size of the rock is important to assess the efficiency of the cutting process of the mechanical excavation machine and the production in mining operations. The degree of rock fragmentation plays an important role in controlling and minimizing the overall production cost.

The size of rock fragments produced in the mechanical excavation with different cutting tools has been studied both in laboratory scale and field scale. The relationships among the size distribution parameters, specific energy, and cutter force has been widely examined (Ozdemir, 1995; Bruland, 2000; Rostami et al., 2002; Altindag, 2003; Kahraman, 2004; Tuncdemir et al., 2008; Farrokh and Rostami, 2008). However, there is lack of information to quantitatively analyze the size distribution of the rock chip produced by rock cutting with a pick cutter and to conclude the relationship between the distribution and the cutting efficiency.

In this study, a series of linear cutting test was performed to investigate the effect of cutting conditions (i.e., cut spacing and penetration depth) on producing of rock chip and the size distribution of the rock chips. All rock chips were collected after LCM (Linear Cutting Machine) test, while the size distribution of the rock chips was analyzed using sieving test and image processing. The relationships among the cutter force, the specific energy, chip size, size distribution parameters were analyzed.

2. Experiments

2.1 Linear cutting machine test

We used a small scaled linear cutting machine (SLCM) system in this study (Figure 1). This system has 20 ton loading capacity and can sustain sufficient stiffness during the linear cutting test. The system consists of the main frame, an electronic motor unit, and a control panel. The main frame features a large stiff frame on which a conical pick is mounted.

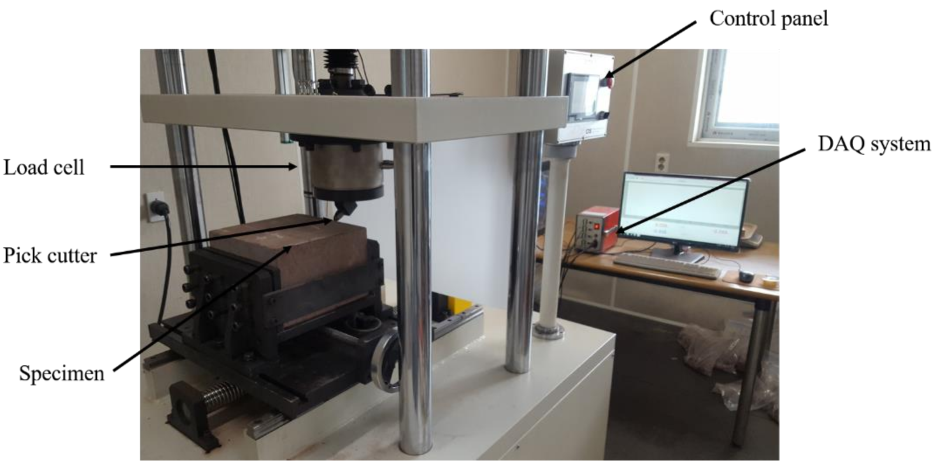


Figure 1. The small scaled linear cutting machine system used in this study

The rock specimen was Linyi Sandstone from China cut into 300 mm x 300 mm x 200 mm for testing purpose. The mechanical properties of Linyi sandstone are presented in Table 1. Linyi sandstone is considered to be isotropic.

Table 1. Mechanical properties of Linyi Sandstone

Properties	Unit	Value
Density	g/cm^3	2.4
Porosity	%	8.2
Uniaxial compressive strength	MPa	64.0
Brazilian tensile strength	MPa	4.7
Young`s modulus	GPa	10.2
Poisson`s ratio		0.2
Schmidt hammer rebound hardness*		57.3
Shore hardness*		43.5
P-wave velocity (m/s)	m/s	2317
S-wave velocity (m/s)	m/s	1531

**Schmidt hammer rebound and Shore hardness values were obtained by averaging the upper ten values from 20 tests performed*

The conical pick (Model: PN 735MB) used in this study was manufactured by Vermeer Corporation as shown in Figure 2. The cutter geometry has the gauge of 40 mm, primary tip angle of 70˚, tip diameter of 12 mm, the flange diameter of 30 mm, and the shank diameter of 18.5 mm.

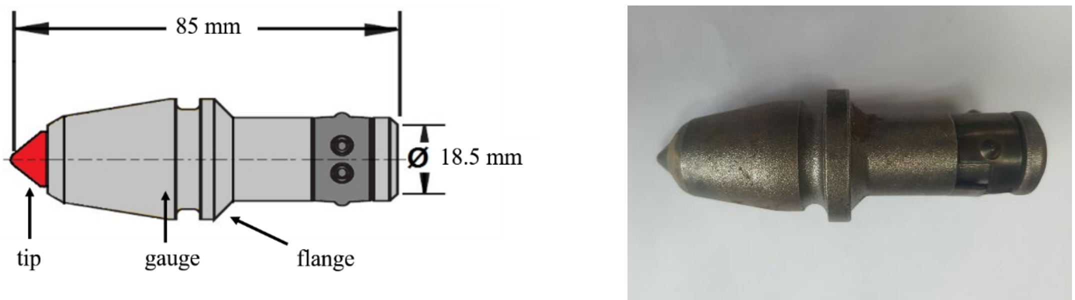


Figure 2. A photograph and schematic drawing of the conical pick used in this study

The skew (θ) and attack (α) angle of the pick cutter were set to 0° and 45°, respectively. The penetration depth (p) was from 5 mm to 11 mm at 2 mm interval. s/p ratio was from 1 to 5, while cut spacing (s) was determined by penetration depth and predetermined s/p ratio. The cutter force, specific energy, and the size distribution were only considered for the relieved cut mode. The constant variables in the testing were cutting sequence (single-start) and cutting speed (10 mm/s). The cutter forces in three directions (normal, cutting and side force) were measured with the load-cell at the sampling rate of 20 s-1. The cutting distance was 200 - 250 mm for all cutting conditions, and the number of cutting lines was at least five for each case.

2.2 Sieve test and image processing

A sieve tester and image processing software were used to obtain a cumulative particle-size distribution curve. This study used SPLIT-DESKTOP for the chip size distribution analysis. The general flow of image processing is as follows: the acquired image was cropped to separate the parts of the rock debris and the unnecessary parts, and the scale was set using the ruler in the image. The image was automatically delineated by the Split desktop to recognize each rock chip. After confirming the auto-delineation results, manually correct any abnormally separated or non-separated rock fragments. Small particles that are difficult to delineate are set as fine material. (Fine factor = 5). Determine the size of sieve set for size distribution analysis, and the sieve size should be set so that all of the rock fragments can be analyzed (at least larger than the biggest rock fragments). After the whole process, we could obtain the result of particle-size distribution.

The countable rock chips was analyzed by the image-processing software, and small particles (named as rock powder in this study) were analyzed using the direct sieve test because it is difficult to delineate each small particle with image processing.

2.3 Determination of size distribution parameters

There are many parameters to describe the chip size distribution. In soil mechanics, the coefficients of uniformity and curvature are usually used to represent the characteristics of particle distribution, and they can be calculated by the effective sizes (D10, D30, and D60) in the cumulative particle size distribution curve. Also, Rosin-Rammler distribution parameters represent the distribution of rock fragments. The uniformity index (N) and the absolute size constant (D) can be defined based on the Rosin-Rammler distribution.

Several studies have introduced and adopted the coarseness index (CI) to quantify the size distribution of rock debris (Roxborough and Rispin, 1973; McFear-Smith and Fowell, 1977; Altindag, 2003; Tuncdemir et al., 2008; Bakar and Gerstch, 2013). The CI is a dimensionless value and is calculated by the sum of the cumulative weight percentages retained on each sieve used. However, the CI is dependent on the sieve size, so it changes according to the sieve size. Thus, the coarseness index can be used to compare the relative characteristics of rock particle sieved by the same set of sieves. In this study, the maximum and the minimum sieve size were 19.1 mm and 1.64 mm in diameter, respectively. Table 2 shows the representative results of the CI.

Table 2. The example of the calculation of coarseness index

Size fraction (mm)	Retained mass (g)	Cumulative mass (%)
+19.1	73.86	16.72
-19.1 +13.2	134.07	47.06
-13.2 +9.28	76.32	64.33
-9.28 +6.56	34.02	72.03
-6.56 +4.64	32.39	79.37
-4.64 +3.28	15.84	82.95
-3.28 +2.32	9.34	85.06
-2.32 +1.64	6.62	86.56
-1.64	47.3	97.27
Total mass	429.76	*CI* = 631.35

3. Results

3.1 Cutter force and specific energy

The cutter force and specific energy in different cutting conditions were summarized in Table 3. The mean cutter forces are the averaged values of the forces obtained the tests. The normal and cutting forces linearly increased with the penetration depth, and the optimum cutting condition was defined as the s/p ratio at the minimum specific energy. The optimum s/p ratios were found to be four for 5 mm of penetration depth and three for other penetration depths. The optimum s/p ratio is decreasing with the increase of penetration depth.

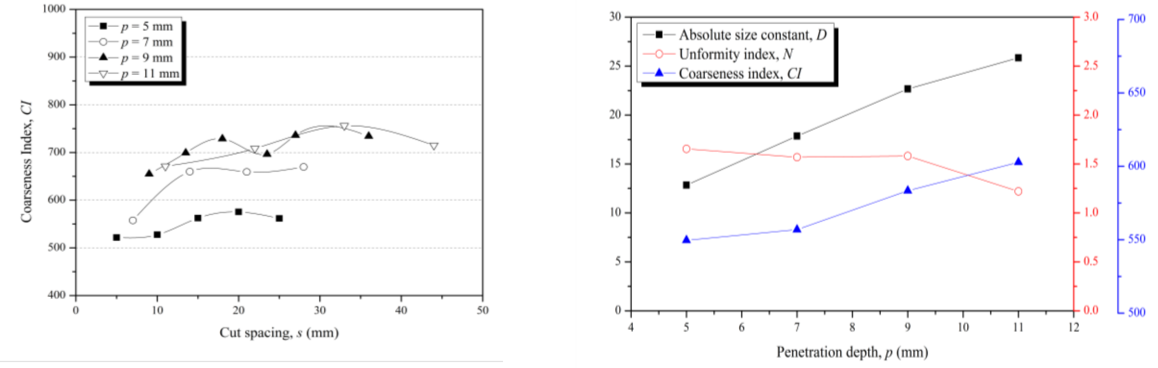
Table 3. Testing condition and the result of LCM test

p (mm)	*s* (mm)	*s/p*	Mean cutter force, F_{mean} (kN)			Specific energy (MJ/m^3)
			Side	Cutting	Normal	
5	5	1	0.81	3.21	3.61	82.96
	10	2	0.13	4.25	4.38	77.65
	15	3	0.17	5.21	5.29	77.86
	20	4	0.53	5.81	5.87	67.57
7	7	1	0.47	3.48	3.51	54.74
	14	2	0.54	5.08	5.13	48.94
	21	3	0.61	6.07	6.84	42.17
	28	4	0.84	6.96	7.25	44.94
9	9	1	0.60	5.02	5.65	49.73
	18	2	0.52	6.63	7.96	37.69
	27	3	0.52	7.59	9.40	33.12
	36	4	0.78	8.30	10.95	39.70
11	11	1	0.26	6.97	7.29	46.30
	22	2	0.63	7.93	8.39	34.39
	33	3	1.27	8.90	9.64	31.10
	44	4	1.30	10.02	12.96	32.71

3.2 Chip size and distribution

In this study, all rock chips generated in a linear cutting test were collected to analyze their size distribution as mentioned above. The size of the rock chips increased significantly at the optimum cutting spacing, and the representative sizes of rock chips in each penetration depth are 20 mm × 35 mm, 27 mm × 45 mm, 35 mm × 55 mm, 75 mm × 45 mm, respectively. As the cut spacing increased, the size of the rock chip also gradually increased. The size of rock chip was the greatest at the optimum cut spacing. The maximum chip size appeared at the 11 mm of penetration depth and 33 mm of cut spacing.

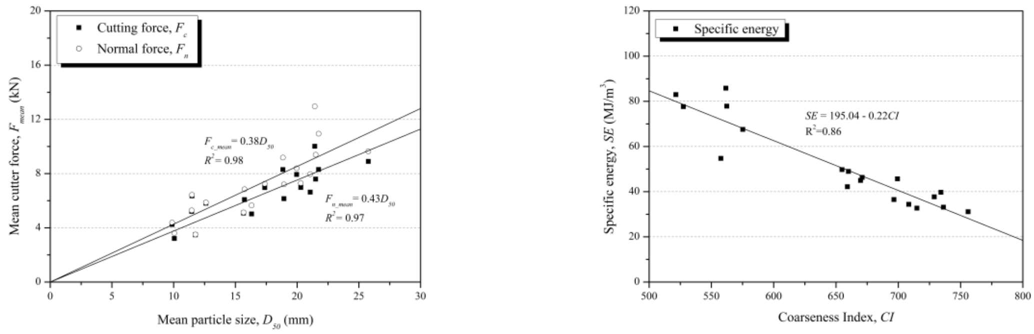
Figure 3 (a) shows the effect of the cut spacing on the particle size which was represented by coarseness index. The result shows that the coarseness index tends to maximize where the cut spacing was at the optimum condition at the different penetration depths. Figure 3 (b) shows the effect of the penetration depth on the characteristic of particle size and its distribution. It is clearly found that the larger penetration depth, the larger size of the rock chip is produced, and the distribution has the lower uniformity. In addition, the particle size and its distribution are more dependent on the penetration depth than the cut spacing. Based on the rock cutting theory, it is well-known the maximized rock fragmentation induces the efficient rock-cutting. Thus, the results supported that the operational condition with the deep penetration depth is efficient cutting condition.



(a) Cut spacing (b) Penetration depth

Figure 3. The relationship between size distribution parameter (a) cut spacing and (b) penetration depth

Figure 4 (a) shows the relationship between the cutter forces and the mean particle size (D_{50}). The cutter forces (normal and cutting) linearly increased with the mean particle size. The results indicate that the larger cutter force was required to cut the rock into larger debris. Figure 4 (b) shows the relationship between coarseness index and specific energy. The relationship also indicates the cutting condition with the larger coarseness index is more efficient.



(a) Cutter force (b) Specific energy

Figure 4. The relationship between chip size distribution parameter (a) cutter force, and (b) specific energy

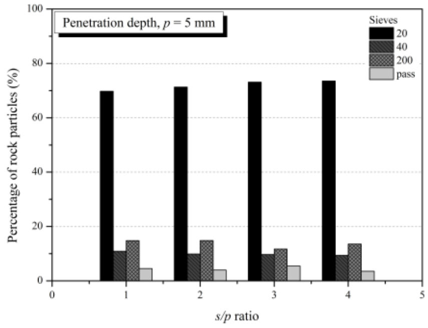
3.3 Rock powder proportion

Observing rock cutting mechanism, compressive stress concentration occurs directly under the cutter in contact with the rock, so that the rock in that part is crushed into rock powder (very fine material) rather than rock chips. It is not preferable to increase the proportion of rock powder in mining by mechanical excavation because rock powder is more difficult to recover than rock chips. Especially when working in subsea, rock powder meets with water and produce slurry, which increases the required cutter force and causes the cutting efficiency to decrease (Jackson et al., 2007).

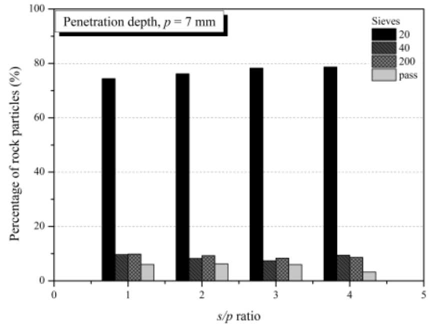
In this study, the volume of the rock fragments obtained after the cutting test was classified into rock powder and rock chip. There are many available standards to classify soil particles depending on the size, while the Unified Soil Classification System (USCS) is generally adopted for the classification of the soil particles. In this study, the particles less than 2 mm in diameter were defined as rock powder according to the classification system.

Figure 5 shows the distribution of the rock particles sieved by #20 (2 mm), #40 (0.4 mm) and #200 (0.0675 mm) mesh of standard sieves according to the cut spacing and the penetration depth. The result indicates that the proportion of the rock particles sieved by each sieve (with respect to the total mass) is consistent with cut spacing. As shown figure 5, the percentage of rock powder for the total weight of cut rock at the 5 mm, 7 mm, 9 mm and 11 mm of penetration depths were 28.1% (26.5 ~ 30.3%), 23.1% (21.3 ~ 25.6%), 15.9% (10.2 ~ 19.9%) and 11.5% (9.5 ~ 13.0%), respectively, on average. In addition, the percentage of rock powder for significant chip at the 5 mm, 7 mm, 9 mm and 11 mm of penetration depths were 39.5% (36.0 ~ 43.4%), 30.1% (27.1 ~ 34.37%), 19.2% (11.4 ~ 24.9%) and 12.0% (10.5 ~ 14.9%), respectively.

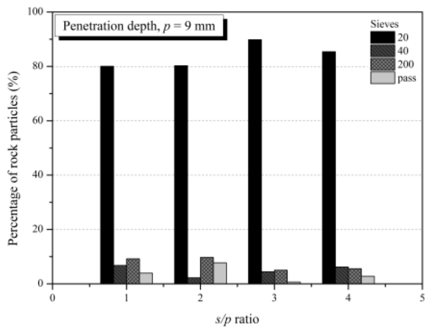
The ratio of rock powder tended to decrease linearly with the penetration depth (Figure 6). The results are reasonable; the possibility of producing a large size chip increases as the penetration depth increases. However, because the limited penetration depths were considered in this study, the discussion for the deeper penetration depths need to made in further studies.



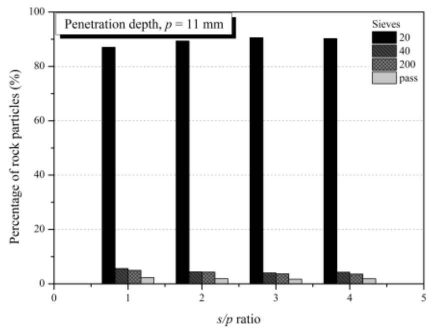
(a) p = 5 mm



(b) p = 7 mm



(c) p = 9 mm



(d) p = 11 mm

Figure 5. The distribution of the sieved rock particles according to the penetration depth and the cut spacing

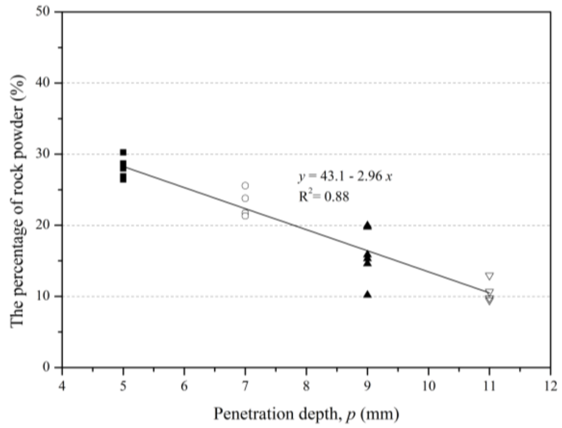


Figure 6. The percentage of rock powder according to the penetration depth

Since rock chips are created by the interaction of cracks between adjacent cutters, the larger the mass of the chipped rock and the larger the chip size, the more efficient the cutting was made. On the contrary, rock powder is produced by the high level of compressive stress in the crushed zone. Therefore, the proportion of rock powder in the total volume of cut rock is an indicator to estimate cutting efficiency. The higher the ratio of rock powder is obtained, the more inefficient the cutting is made.

4. Conclusions

In this study, a series of linear cutting test was performed to investigate the effect of cutting conditions (i.e., cut spacing and penetration depth) on producing of rock chip and the size distribution of rock chips. The relationship between the chip size distribution parameter and the cutter force and the specific energy were investigated using image processing technique and sieving analysis. It was observed that the cutter force increased with the size of rock chip. The results from in this study also indicate that the coarseness index, mean particle size and the absolute size constant are highly correlated with the specific energy. Thus, the particle size and its distribution produced by rock cutting directly indicate rock cutting efficiency. This means that the size of the rock chip can also be used as an index of cutting efficiency, and it will be necessary to build a database of experimental results and field practices with more rock types and cutting conditions.

The proportion of rock powder of the excavated volume is analyzed. The rock powder (diameter less than 2 mm) in the crushed zone were highly correlated with the specific energy. Also, the ratio of rock powder was found to be more than 20% at the considered cutting conditions. The results showed that the ratio of rock powder in the cutting volume can be changed from 20% to 50% depending on the penetration depth and the cut spacing. The ratio can be reduced by the increase of the penetration depth. The results of this study can be used to optimize the cutting efficiency and to determine the optimum particle size for efficient processing of mineral resources in mining engineering application.

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